RISK/BENEFIT ANALYSIS

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The importance of perceptions of risks is illustrated by Table 1-1, which summarizes results of a public opinion survey. Most people seem to believe that life is becoming more dangerous, even though most objective measures show the contrary to be true. The expectation of life, for example, an inverse measure of the probability of dying, has steadily increased, from perhaps twenty-eight years fifteen centuries ago, to fifty years one century ago, to about seventy-two years currently, although the rate of increase has been decreasing. The increase has been brought about by the elimination of many large risks to life, among them many infectious and contagious diseases, poor working conditions, and inadequate nutrition. Figure 1-1 shows the reduction in death rates in this century by age group. Detailed examination shows that the increase since 1960 in the 15 to 24 age group is due to automobile accidents. Doll (1979) has also shown how health, as measured by most medical indicators, is improving. It is now necessary to concentrate on the many smaller risks, often poorly understood, in order to further reduce total risks. Perhaps it is

Table 1-1. Public Opinion Survey Comparing Risk Today to Risk of Twenty Years Ago.

Q: Thinking about the *actual amount of risk* facing our society, would you say that people are subject to more risk today than they were twenty years ago, less risk today, or about the same amount of risk today as twenty years ago?

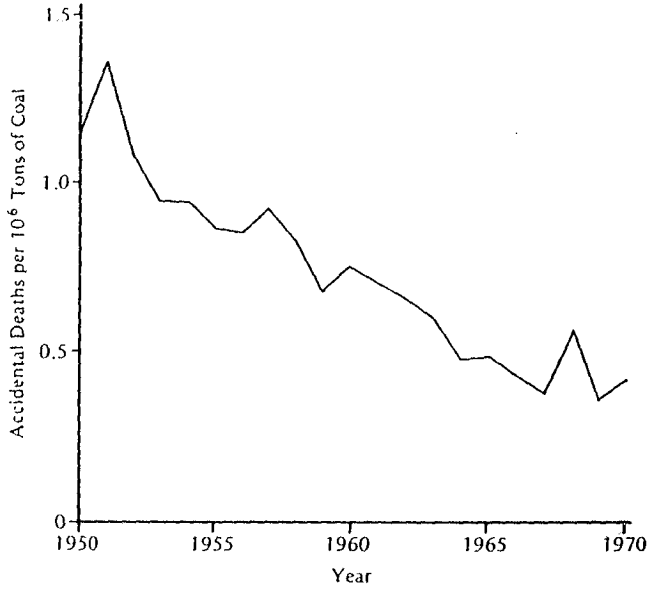
Q: I'd like to start by asking you a few questions about the amount of risk we face in our day-to-day living. Thinking about the *actual amount of risk* facing our society, would you say people are subject to more risk today than they were twenty years ago, less risk today, or about the same amount of risk today as twenty years ago?

	Top Corporate Executives (N = 401)	*Investors, Lenders (N = 104)*	*Congress (N = 47)*	*Federal Regulators (N = 47)*	*Public (N = 1,488)*
			(percent)		
More risk	38	60	55	43	78
Less risk	36	13	26	13	6
Same amount	24	26	19	40	14
Not sure	1	1	...	4	2

Source: Marsh & McLennan Companies (1980).

Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000

Figure 2-1. Accidental Deaths per Million Tons of Coal Mined in the United States.



What measures of risk are appropriate for a particular risk assessment depend on the specific details of the question the assessment is designed to illuminate. Presumably they will be the measures corresponding as nearly as possible to the way in which the risks are perceived. In what follows we will usually be limiting consideration to risks of death (measured by probabilities of dying or expected excess numbers of deaths) resulting from various actions, although other risks will occasionally be mentioned.

Although we shall not concern ourselves much with it, the distinction between risks and measures of risk is not totally academic. A simple example is the American coal industry, taken as a whole, between 1950 and 1970. Figure 2-1 is a plot of one measure of risk in this industry—the number of accidental deaths per million tons of coal mined. Clearly this measure steadily declined during this period, so that, if we follow the industry through successive years, it appears to be getting safer. Looking at Figure 2-2, which shows the behavior of another measure of risk—the number of accidental deaths per

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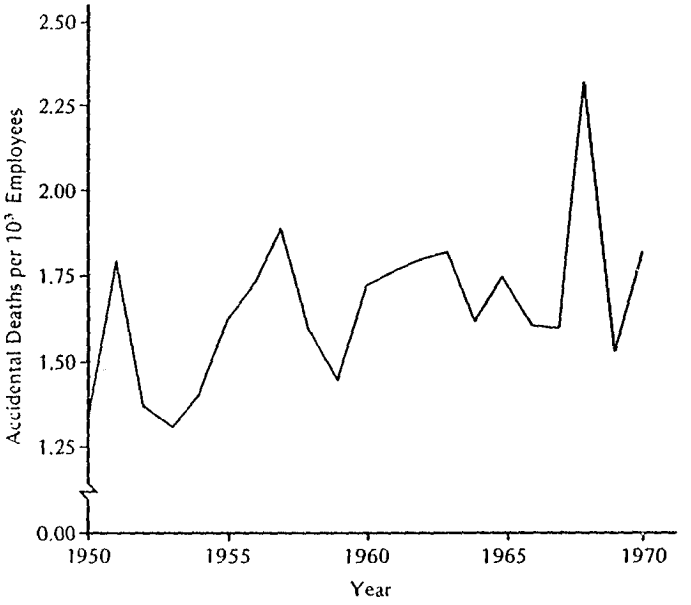
Figure 2-2. Accidental Deaths per Thousand Coal Mine Employees in the United States.



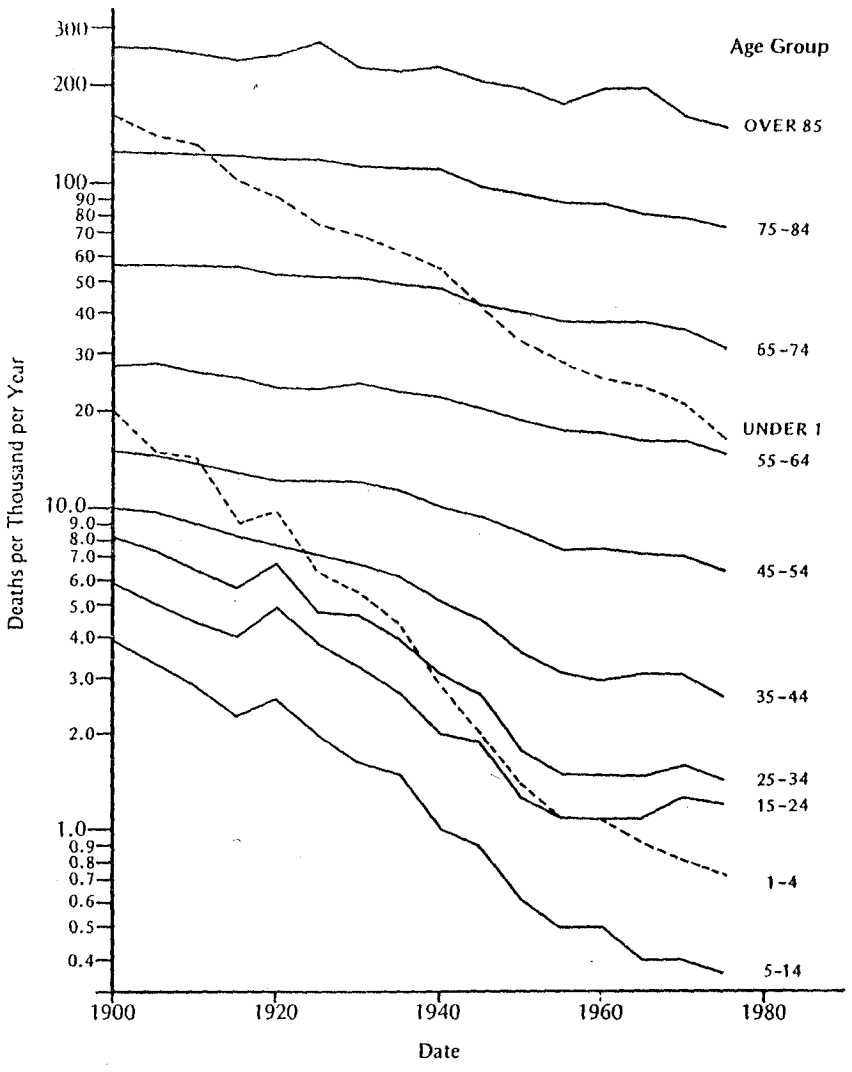
thousand persons employed—one might naively assert that the industry is getting more dangerous, not safer.

Evidently the two measures illustrated might be used to support opposing views on the safety of coal mining. Neither measure taken alone is right or wrong, nor are they even contradictory even though they may be so perceived. Any risk assessment supposed to be complete would have to draw attention to the two aspects of the risk of coal mining gauged by the two different measures and would have to take both into account, depending exactly on the purpose of the risk assessment. From a national point of view, given that a certain amount of coal has to be obtained, deaths per million tons of coal is the more appropriate measure of risk, whereas from a labor leader's point of view, deaths per thousand persons employed may be more relevant.

What steps to take to reduce the risk will depend on which of the two measures is used. Doubling the number of miners, each working

Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000

Figure 1-1. Death Rates at Five Year Intervals from 1900 to 1975 for Various Age Groups: United States.



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mum from some point of view. One attempt at reducing such possibilities is the objective analysis of risk, which is pursued throughout this book.

To make any start on objective assessment it is necessary to realize what is being measured. Death is one clear objective measure. The total annual risk of death at any age is just the probability of dying within one year. In the absence of any extra causes, population averages for this measure are obtained from national mortality tables (see Chapter 7). But in risk assessments we are interested in additional risks of death or components of the total risk of death due to some specific actions undertaken either voluntarily or involuntarily. More often, we are interested in how much of an action to undertake, so that we wish to evaluate measures such as extra probability of death per unit of action (per cigarette smoked, or per ton of coal mined, for example).

Death is not the only measure of risk of interest, for, although it is probably the most objective one and for this reason often used, it may not capture large components of what are perceived as risks. In balanced decisions it may become vital to consider other measures. A few possible such measures are:

- Deaths
  - by age
  - by cause
  - ...
- Injuries
  - by cause
  - by type
  - by severity index
  - ...
- Illness
  - by cause
  - by type
  - by severity index
  - ...
- Man-days lost
  - by cause
  - ...
- Days of impaired health
- Days of pain
- Loss of life expectancy

Each of the above may be measured as:

- Total numbers (whole task) or probabilities (for individuals)
- per unit operation size
- per event
- per unit dose (per cigarette, per ton produced, per unit output, etc.)

Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000

This form of analysis constitutes an all-at-once technique, but one that is less useful than the preceding example (chemical hazards) because it gives no clue as to how to reduce the risks. The limitation can be overcome if it is possible to analyze each event leading to risks as a sequence of well-understood events forming an event tree. A set of event trees would cover all possible cases leading to the final risky event.

The most well-known use of event tree analysis is, perhaps, the analysis of nuclear reactor accidents in the so-called Rasmussen report (Nuclear Regulatory Commission 1975). The procedure will be briefly outlined here with a highly simplified example from the report. The first step is identification of all possible sequences of events that may lead to serious consequences to public health and safety, followed by the separation of these sequences into segments that are approximately independent of each other. By analyzing each event in each sequence separately, using theory or past experience or both, the overall probability of occurrence of the whole sequence can be evaluated. Thus the most probable (highly simplified) sequence for catastrophic failure in a PWR is shown in Figure 3-6. The overall accident probability (with assumptions to be mentioned) is then equal to

Probability of a pipe break (from theory and past data on other pipes)
× probability of failure of emergency core cooling system (from a fault tree analysis)
× probability of containment violation (more fault trees)
× probability of unfavorable weather (past data on wind patterns, rainfall, and so on)
$= p_1\ p_2\ p_3\ p_4$.

The accident described by this event tree is initiated by the break of a water pipe in the cooling system causing loss of coolant and resulting, if the emergency core cooling system subsequently fails, in the meltdown of the reactor core and the release of the fission products therein. This may cause a violation of the concrete containment vessel, so that if the wind direction is right the released fission products may be blown over population centers, possibly causing radiation overdoses to a large segment of the population. In each case the probability of the event and also its severity must be evaluated. As indicated, the probability (p_1) of a pipe break may be estimated from historical experience with pipes first in other industries, sec-

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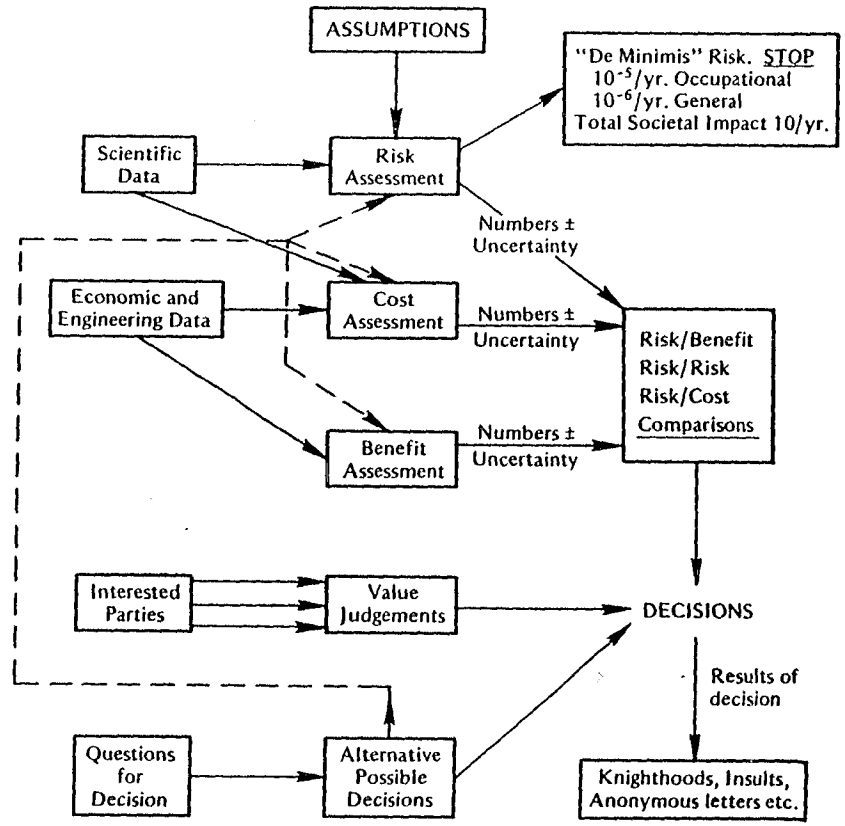
cases are examined in detail major flaws and weaknesses can be discovered. We are heartened, however, by the realization that many of the flaws can easily be remedied and that in at least one case (saccharin) common sense filled in the gaps.

Before beginning a detailed discussion of individual studies, it is useful to picture an idealized scheme (Figure 6-1) of the complete decision process, and the place of risk assessment within it. Information is passed from scientist, engineer, and economist to risk assessor and to cost and benefit assessors. The results of these assessments and comparisons between them are made available to the decision-

Figure 6-1. Idealised Scheme for Risk Analysis.



Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000

Table 7-1. Some One in a Million Risks.

Living in the United States: Time to accumulate a one in a million risk of death from the cause indicated.

Motor vehicle accident	1.5 days
Falls	6 days
Drowning	10 days
Fires	13 days
Firearms	36 days
Electrocution	2 months
Tornadoes	20 months
Floods	20 months
Lightning	2 years
Animal bite or sting	4 years

Occupational Risks. Time to accumulate a one in a million risk of death in the occupation indicated.

General

Manufacturing	4.5 days
Trade	7 days
Service and Government	3.5 days
Transport and Public Utilities	1 day
Agriculture	15 hours
Construction	14 hours
Mining and Quarrying	9 hours

Specific

Coal Mining (accidents)	14 hours
Police duty	1.5 days
Railroad Employment	1.5 days
Fire Fighting	11 hours

Other Risks.

Cosmic Rays.

One transcontinental round trip by air.
Living 1.5 months in Colorado compared to New York.
Camping at 15,000 feet for 6 days compared to sea level.

Other Radiation

20 days of sea level natural background radiation.
2.5 months in masonry rather than wood building.
1/7 of a chest X-ray using modern equipment.

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Table 7-1. continued

Eating and Drinking.

40 diet sodas (saccharin)
6 pounds of peanut butter (aflatoxin).
180 pints of milk (aflatoxin).
200 gallons of drinking water from Miami or New Orleans.
90 pounds of broiled steak (cancer risk only).

Smoking

2 cigarettes

Source: Tables 7-2 to 7-5.

clearly into categories within which intercomparison is more easily justified and probably more accurate. Table 7-2 is a list of various commonplace risks of death, most of which would be considered involuntary. Notice that there may be some overlapping between categories (*home accidents*, for example, includes falls within the home). Table 7-3 shows some occupational risks, mostly risks of fatal accidents. Again, most such risks would be considered involuntary by those exposed. Table 7-4, in contrast, shows a set of voluntary risks of death, those incurred in sporting activities. Table 7-5 is a further set of everyday risks, but now specialized to cancer risks, selected because such risks arouse particularly strong emotions.

Before discussing these risks in more detail and indicating how they are all estimated, we would like to give another example that may help place these risks in perspective. Four tablespoons of peanut butter per day is shown as giving a risk of liver cancer of 8×10^{-6} per year, or a lifetime risk of 6×10^{-4}. But four tablespoons of peanut butter corresponds to 400 kilocalories (Kcal), so if one were to eat only peanut butter, daily energy requirements would be supplied by 26 tablespoons per day, giving a lifetime liver cancer risk of 4×10^{-3}, or 0.004. This should be compared with a lifetime probability of any kind of cancer of about 0.25, even in the absence of peanut butter.

Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000

Table 7-2. Some Commonplace Risks of Death in the United States, Based on Estimated U.S. Resident Population (*Source 1*).

Risk	*Annual per Capita Risk*[a]	*Annual Trend*[b]	*Variability, Percent*[c]	*Based On*	*Source*
Motor vehicle accident					
Total	2.4×10^{-4}	...	10	1950-78	1
Collision with pedestrian	4.2×10^{-5}	-3.9×10^{-7}	10	1950-78	2
Home accidents[d]	1.1×10^{-4}	-2.9×10^{-6}	5	1950-78	2
Falls	6.2×10^{-5}	-3.0×10^{-6}	6	1963-77	2
Drowning	3.6×10^{-5}	...	7	1963-77	2
Fires	2.8×10^{-5}	-1.0×10^{-6}	5	1963-77	2
Inhalation and ingestion of objects	1.5×10^{-5}	...	10	1968-77	2
Firearms	1.0×10^{-5}	-2.4×10^{-7}	8	1968-77	2
Accidental poisoning					
Gases and vapors	7.7×10^{-6}	...	5	1963-77	2
Solids and liquids (Not drugs or medicaments)	6.0×10^{-6}	...	10	1971-77	2
Electrocution	5.3×10^{-6}	...	5	1971-77	2
Tornadoes	6×10^{-7}	...	100	1950-77	1
Floods	6×10^{-7}	...	100	1950-77	1
Lightning	5×10^{-7}	...	18	1971-77	2
Tropical cyclones and hurricanes	3×10^{-7}	...	160	1952-77	1
Bites and stings by venomous animals and insects	2.4×10^{-7}	...	13	1971-77	2
Air Pollution	2.4×10^{-4}	...		—see text—	

a. Average over indicated years, if no trend is shown. The value of trend line in last year of indicated years is used if a trend is shown.

b. Average annual change of annual per capita risk during years shown. Least squares straight line fit of annual risk versus time. A trend is shown if the estimated trend was significant at the 5 percent level (two-tailed).

c. Estimated standard deviation of annual per capita risk about the trend line (trend) or of the mean value (no trend).

d. Home accidents includes some proportion of some of the following seven risks.

Sources: 1. U.S. Bureau of the Census (1975, Annual). 2. National Safety Council (Annual).

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Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000

Table 7-3. Some Occupational Risks of Death.

Occupation or Industry	*Annual Risk*[a]	*Annual Trend*[b]	*Variability, Percent*[c]	*Based On*	*Source*
Manufacturing	8.2×10^{-5}	-1.6×10^{-6}	8	1955-78	1
Trade	5.3×10^{-5}	-2.3×10^{-6}	15	1955-78	1
Service and government	1.0×10^{-4}	-2.0×10^{-6}	8	1955-78	1
Transport and public utilities	3.7×10^{-4}	. . .	16	1955-78	1
Agriculture[d]	6.0×10^{-4}	. . .	9	1955-78	1
Construction	6.1×10^{-4}	-7.0×10^{-6}	6	1955-78	1
Mining and Quarrying	9.5×10^{-4}	. . .	22	1955-78	1
Farming[e]	3.6×10^{-4}	-5.0×10^{-6}	7	1964-77	1, 2
Tractor fatalities per tractor	8.8×10^{-5}	-1.0×10^{-5}	22	1969-77	1
Metal mining and milling	9.4×10^{-4}	. . .	15	1959-71	3
Nonmetal mining and milling	7.1×10^{-4}	$+2.3 \times 10^{-5}$	15	1959-71	3
Stone quarries and mills	5.9×10^{-4}	. . .	20	1959-71	3
Coal mining (accidents)	6.3×10^{-4}	-1.0×10^{-4}	46[f]	1963-77	4
Police officers killed in line of duty					
Total	2.2×10^{-4}	. . .	19	1975-78	4
By felons	1.3×10^{-4}	-2.1×10^{-5}	8	1975-78	4
Railroad employees	2.4×10^{-4}	-6.0×10^{-6}	7	1963-77	1, 4
Steel worker (accident only)	2.8×10^{-4}	. . .	?	1969-72	5
Fire fighter	8.0×10^{-4}	. . .	?	1971-72	5

a. Per person at risk. Average over indicated years, if no trend is shown. The value of trend line in last year of indicated years is used if a trend is shown.

b. Average annual change of annual risk during indicated years. Least squares straight line fit of annual risk versus time. A trend is shown if the estimated trend was significant at the 5 percent level. Note that the error estimates for these trends are generally large.

c. Estimated standard deviation of annual risk about the trend line (trend) or of the mean value (no trend). Expressed as a percentage of the risk shown in the first column.

d. Not strictly comparable with farming category, includes transport accidents and all agriculture.

e. Not strictly comparable with agriculture category, refers to nontransport deaths occurring on farms, the population at risk being assumed to be all employed workers, unpaid family members working more than fifteen hours per week and operators working more than one hour per week.

f. The large variability is due to the bad choice of model (straight line fit) and the large changes occurring in the years indicated.

Sources: 1. National Safety Council (Annual). 2. U.S. Department of Agriculture (1979). 3. U.S. Bureau of Mines (Annual). 4. U.S. Bureau of the Census (Annual). 5. Baldewicz et al. (1974).

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Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000

Table 7-4. Annual Fatality Risks in Sports.[a]

Sport	Average Annual Risk[b]	Average Annual Deaths	Estimated Population at Risk	Years of Coverage	Source
Aerial acrobatics (professional)	$\lesssim 2 \times 10^{-3}$ d,h	0.22	360	1970-78	1
Air show/air racing and acrobatics	5×10^{-3}	4.9	1,050[c]	1971-77	1
Flying amateur/home built aircraft	3×10^{-3}	25	8,000[c]	1970-77	1
Bicycle racing (registered)	$\lesssim 9 \times 10^{-5}$ d,e	0.33	9,800	1970-78	1
Boating	5×10^{-5}	1,300	27×10^6	1972-78[j]	2, 3
Bobsledding	$\lesssim 7 \times 10^{-4}$ d,f	0	450	1970-78	1
Football					
Sandlot	2×10^{-6}	1.7	10^6	1970-78	1
Professional and Semiprofessional	$\lesssim 4 \times 10^{-4}$ d,g	0.11	1,500	1970-78	1
High school	1×10^{-5}[l]	13	10^6	1970-78	1
College	3×10^{-5}[l]	1.2	40,000	1970-78	1
Glider flying	4×10^{-4}	7	18,000[c]	1970-77	1
Hang gliding	$\sim 8 \times 10^{-4}$	31	20,000-60,000	1974-78	1
Hunting	3×10^{-5}	600-800	22×10^6	1972	2, 3
Ice yachting	$\lesssim 1 \times 10^{-4}$ d,h	0.22	4,500-6,500	1970-78	1
Lighter-than-air flying	9×10^{-4}	2.6	3,000[c]	1970-77	1
Mountaineering	6×10^{-4}	34	60,000	1970-78	1
Mountaineering[k]	7×10^{-4}	12	19,000	1951-60	4
Power boat racing	8×10^{-4}	5.2	6,500	1970-78	1
Professional stunting	$\lesssim 1 \times 10^{-2}$ d,i	1	200	1975-78	1
Rodeo	$\lesssim 3 \times 10^{-5}$ d,e	0.33	34,000	1970-78	1
Scuba diving	4×10^{-4}	126	300,000	1970-76	1
Ski racing	2×10^{-5}	2	81,000	1970-78	1
Spelunking	$\lesssim 1 \times 10^{-4}$ d,i	0.44	10,000	1970-78	1
Sport parachuting	2×10^{-3}	41	25,000	1970-78	1
Thoroughbred horseracing	1×10^{-3}	2.6	1,800	1970-78	1
Swimming	3×10^{-5}	2,600	82×10^6	1972-78[j]	2, 3

a. No error estimates are given. The reason is that, although we could give statistical sampling errors on the risks shown, the population size is so uncertain in most cases (by a factor of 2 to 3) that this uncertainty dominates.

b. Per person at risk. See preceding note on error estimates.

c. This population corresponds only to pilots certified by the Federal Aviation Administration.

d. The value shown is statistical 95 percent confidence upper bound, assuming risk proportional to person-years of exposure and a Poisson distribution of deaths. See also note *a* on error estimates.

e. Three deaths observed in time indicated.

f. No deaths observed in time indicated.

g. One death observed in time indicated.

h. Two deaths observed in time indicated.

i. Four deaths observed in time indicated.

j. Population figures from 1972, deaths from 1978. We have assumed a similar population went swimming or boating in 1978.

k. Not strictly comparable with the preceding entry, also labeled *Mountaineering*. The figure in the population column is total man-mountain-days, and the risk is per man-mountain-day. This agrees with the previous figure for annual risk if an average of ~ 0.9 days per year is spent mountaineering, but note that the years of coverage differ also.

l. If participation has remained constant, as we assume, there are possibly decreasing trends in these risks.

Sources: 1. Metropolitan Life Insurance Company (1979). 2. U.S. Bureau of the Census (Annual). 3. National Safety Council (Annual). 4. Fers (1963). (The article also discusses some of the problems of interpretation of risks such as those shown in this table).

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Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000

Table 7-5. Everyday Cancer Risks.[a]

	Annual Average Risk[c]	Estimated Uncertainty[d]	Source
Current Cancer Rates[b]			
All Cancers	2.8×10^{-3}		
Buccal cavity, pharynx, respiratory	7.2×10^{-4}		
Digestive organs and peritoneum	7.5×10^{-4}		
Bone, connective tissue, skin, breast	3.1×10^{-4}	~ 20%	1
Genital organs	3.2×10^{-4}		
Urinary tract	1.2×10^{-4}		
Other	2.7×10^{-4}		
Leukemia and other blood and lymph	2.6×10^{-4}		
Cosmic Ray Risks[f]			
Airline pilot (50 hours per month at 12 kilometers altitude)	4×10^{-5}		2
One transcontinental round trip by air per year	10^{-6}		2
Frequent airline passenger (4 hours per week flying)	10^{-5}		2
Living in Colorado compared to New York	8×10^{-6}	Factor of 3[f]	3
Camping at 15,000 feet for 4 months per year	2×10^{-5}		3
Other Radiation Risks			
Natural background radiation (sea level)	2.0×10^{-5}		3
Average diagnostic medical X-rays in the United States	2.0×10^{-5}		4
Living in masonry building rather than wood	5.0×10^{-6}		5
Eating and Drinking			
One 12½ ounce diet drink per day	10^{-5}		
Average saccharin consumption in the United States	2.0×10^{-6}		
Four tablespoons peanut butter per day[i]	8.0×10^{-6}	Factor of order 10	See text.
One pint milk per day[i]	2.0×10^{-6}		
Miami or New Orleans drinking water	10^{-6}		
½ lb. charcoal broiled steak per week (cancer risk only; heart attack and other risks additional)	3.0×10^{-7}		
Alcohol, averaged over smokers and nonsmokers[g]	5.0×10^{-5}	Factor of order 10	See text.
Alcohol, light drinker (one beer per day)[g]	2.0×10^{-5}		
Tobacco[h]			
Smoker, cancer only	1.2×10^{-3}	Factor of 3	See text.
Smoker, all effects (including heart disease)	3.0×10^{-3}		
Person sharing room with smoker	10^{-5}	Factor of 10	
Air Pollution			
Polycyclic organics, all effects	1.5×10^{-5}	See text.	See text.

a. These are risks of death, the difference between incidence and mortality being well within the uncertainties shown, (except for the Current Cancer Rates category.

b. Included to give some perspective. The figures given correspond approximately to the lifetime risk divided by the lifetime. The lifetime risk is estimated by the fraction of those dying who die of the given cancer, average lifetime is estimated as seventy years. Since cancer rates increase rapidly with age and the population age structure is changing, these figures are only approximate. Data from *Vital Statistics of the United States*, 1975.

c. Averaged over the whole population of the United States.

d. Even the uncertainties in these estimates can be very large. The uncertainties are mostly estimated subjectively and are conditional on the models used for extrapolation being approximately correct.

e. Averaged over males and females. The risk is approximately double for females only.

f. We assume a linear model with a total of 1 cancer per 5,000 man-rem, corresponding to BEIR 1972. More recent estimates of the BEIR committee (1980) would give slightly lower estimates.

g. Cirrhosis of the liver. Not a cancer, but included here since the methods used are similar. It is possible that in this case there is a threshold effect for damage. In addition there is some evidence that moderate alcohol consumption is associated with lower death rates from other diseases.

h. Based on human data.

i. Based on human data for aflatoxin carcinogenicity. Note that we assume that the measured aflatoxins are aflatoxin B, the most potent. If it corresponds to other aflatoxins, these estimated risks should be reduced.

Sources: (The following references are the sources of data used in the models. We have estimated the risks). 1. U.S. Department of Health, Education and Welfare (1975). 2. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1962). 3. Oakley (1972). 4. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1977). We have used the bone marrow dose here. 5. Moeller and Underhill (1976).

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Source: https://www.industrydocuments.ucsf.edu/docs/stbl0000